SUMMARY[a]

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This summary is an attempt to overview the wealth of new results and ideas in quarkonium physics presented at the Seattle Workshop.

1 Introduction

After the 1974 discovery of the J/ψ, the hadronic world was never the same. From the very beginning it had been recognized that this particle, with its unusually small width and large mass, was a stand-out in the hadronic zoo. The large mass was soon understood to be the consequence of the existence of a new massive quark flavor, and the small width – the consequence of asymptotic freedom, making the coupling, and therefore, the annihilation probability, small at the scale of the charm quark mass. The understanding of J/ψ properties was therefore crucial for establishing QCD as the standard model of strong interactions.

Seattle Workshop took place at a particularly interesting time for quarkonium physics. The CERN SPS results from NA50 undoubtedly demonstrated that collective phenomena dramatically affect the J/ψ production in Pb-Pb collisions. Fermilab Tevatron results of CDF and D0 made theorists to put under scrutiny the widely accepted color-singlet model of quarkonium production. Fermilab fixed target pA results from E866 for the first time opened a new kinematic window of negative x_F. And, with RHIC experiments at BNL starting to accumulate data next year, we have to carefully analyze the mean-

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ing of the information available to us at present to make predictions for the future.

What follows below is my personal account of the most significant results presented in Seattle; obviously, such a selection is always biased, and I could easily miss something very important. I apologize in advance also for potential misinterpretations of the presented talks – to acquire a proper understanding, the reader is strongly encouraged to read the original contributions in this Volume.

2 What have we learnt at the Workshop?

The naive model of J/ψ as a bound state of charm quark and anti-quark turned out to be only a rough approximation to reality, as **E. Braaten**[1] discussed at this Workshop, and one has to go beyond this model to explain the puzzles which exist not only in quarkonium production, but also in its decays. A particular problem addressed by Braaten at this Workshop was the strong violation of helicity selection rule observed in exclusive decays of J/ψ into $\rho\pi$ final state. The helicity selection rule is a direct consequence of vector coupling of gluons to quarks, and should hold if all of the gluons involved in the process are hard. However, as was pointed out at by Braaten, the presence of dynamical gluons in the J/ψ wave function leads to the possibility of substantial evasion of the helicity selection rule due to the $\bar{Q}Q$ annihilation in the color octet state. It is further argued that a similar evasion does not happen in the ψ' decay as a consequence of the larger weight of the $\bar{D}D$ channel in the wave function, and the significant contribution of this channel depletes the role of the color-octet state at the distances $\sim 1/m_Q$ at which the annihilation takes place. It would be interesting to extend this analysis to other helicity–violating decays, e.g. $\eta_c \to \bar{p}p$. It would also be worthwhile to make a consistency check of the model in radiative decays, such as $\psi' \to \chi\gamma$, which are sensitive to the spatial structure of the ψ' wave function beyond the $\sim 1/m_Q$ distances.

The implications of the color octet model for quarkonium hadroproduction were discussed at this Workshop by **M. Beneke**. The main emphasis in this talk was on a rather crucial issue – does factorization apply to quarkonium hadroproduction? On intuitive level, one expects soft gluon interactions between the $\bar{Q}QX$ system and the remnants of the hadrons to cancel at high p_t, up to corrections on the order of $(\Lambda_{QCD}/p_t)^n$. The total hadroproduction cross section is however dominated by the region of small p_t, and in this region factorization can hold only for sufficiently heavy quarks up to the terms of the order $(\Lambda/m_Q v^2)^k$. If Λ in this estimate is $\Lambda \simeq \Lambda_{QCD}$, the ratio $(\Lambda/m_Q v^2) \simeq 1/3$

for J/ψ, which makes factorization questionable. Moreover, one may expect that the parameter Λ is actually proportional to the strength of the color field/density of partons produced in the collision, and this would make factorization in inclusive J/ψ production even more questionable. The issue becomes really crucial in nucleus-nucleus collisions at high energies, where the number of produced partons which can interact with the $\bar{Q}QX$ system becomes very large. Needless to say, it is very important to verify factorization in quarkonium production, for example, by a more detailed comparison of hadro- and photo-production of J/ψ, including the polarized production to get rid of some of the uncertainties in the values of the color octet matrix elements.

The 1987 discovery of J/ψ suppression in nucleus-nucleus collisions by the NA38 Collaboration excited a lot of interest, to large extent because of the prediction [2] that this suppression would signal deconfinement, and would prove a highly non–trivial phase structure of QCD. The history of J/ψ suppression, as summarized by **H. Satz** at this Workshop, is a very dramatic one. Eventually, after a lot of controversy, the high-quality pA data allowed to establish that, as was advocated by some theorists shortly after the NA38 results were announced, the observed in S-U collisions J/ψ suppression can be explained in a very mundane way by what is often called the "J/ψ absorption". I put this expression in quotation marks, because, at a closer look, none of the words used to describe this phenomenon are correct: i) the fact that $\psi'/J/\psi$ ratio in pA does not depend on atomic number at positive x_F *proves* that what is "absorbed" is not a physical J/ψ; ii) the $c\bar{c}$ pair cannot be really "absorbed" by nucleons – the only thing that can cause the observed J/ψ depletion is a reduction of the probability that the pair will form a J/ψ, accompanied by an increased yield of open charm mesons[b].

I would like to stress that the high quality pA data are absolutely necessary to understand the physical meaning of the effect observed in nuclear collisions. Fortunately, the pA data become more and more accurate and extend to the kinematic region which was not explored before – the new data from Fermilab E866 were presented at the Workshop by **M. Leitch**. For the first time, the E866 Collaboration are able to measure J/ψ's and ψ''s in the negative x_F window – down to $x_F \simeq -0.15$. What we see through this window is exciting – the $\psi'/J/\psi$ ratio, which was known to be independent of the atomic number, starts to drop toward negative x_F. I cannot refrain from saying that this is exactly what was predicted to happen (see e.g. Ref. [3] and Fig.2 in Ref. [4]) – at negative x_F, the $\bar{c}c$ pair becomes slower, and starts to form inside the

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[b]Unfortunately, since the J/ψ yield is only a tiny fraction of the open charm one, this small increase in the production of open charm would be extremely difficult, if not impossible, to establish.

nuclear target. Since the ψ' is much larger than the J/ψ, it is absorbed with a larger probability, and the $\psi'/J/\psi$ ratio drops. It now looks possible to extract the formation time of the pair directly from the data; a superficial first look suggests the proper formation time of $\tau \sim 0.3$ fm. One of the top priorities for the theorists now is to understand the detailed shape of the J/ψ and ψ' distributions in the entire range of x_F; we no longer have an excuse of insufficient data. The current state of affairs in explaining these distributions can hardly be considered satisfactory – usually one has to invoke an eclectic mix of different mechanisms, such as shadowing, absorption, energy loss etc, the magnitude of each of which is poorly known.

The J/ψ production in proton–nucleus collisions and the role of the color-octet mechanism in $\bar{c}c$ absorption were discussed at this Workshop by **C.-Y. Wong** and **X.-F. Zhang**. This is clearly a very interesting problem which is central to the understanding of "conventional" background to the J/ψ suppression. In both talks, the absorption was considered as arising from the interaction of $\bar{c}c$ pair both in the color-octet and color- singlet states. The incoherent mixture of these states was assumed in both talks, with the survival probability

$$S_A = f_1 \ exp(-L\rho\sigma_{abs}^1) + f_8 \ exp(-L\rho\sigma_{abs}^8), \tag{1}$$

where $f_{1,8}$ are the fractions of J/ψ coming from the color-singlet and color-octet mechanisms, and $\sigma_{abs}^{1,8}$ – the corresponding absorption cross sections of the $\bar{c}c$ pair, ρ – mean nuclear density and L - the mean path of the pair in nuclear matter. This assumption may be questioned since the color exchanges between the pair and the nuclear medium will rotate the color polarization vector of the pair as it traverses the nucleus. The mixture of the color-octet and color-singlet components in the $\bar{c}c$ wave functions will therefore become coherent, and the whole problem becomes a classical case for a coupled channel calculation.

Let me come now to the CERN Pb-Pb results from the NA50 Collaboration. **E. Scomparin** presented at this meeting intriguing new data on "intermediate mass enhancement" in the dilepton spectra. We have seen a rather dramatic, up to a factor of 3, (compared to the pA collisions) enhancement of the intermediate mass (below J/ψ) dilepton yield in central Pb-Pb collisions. The origin of this enhancement is unknown; one of the explanations discussed by Scomparin was the enhancement of open charm, manifesting itself, through leptonic decays, in the enhancement of dilepton yield. If this were indeed true, the consequences of this phenomenon would be far–reaching – we would have to accept an extremely strong (a factor of 3!) violation of factorization in the heavy quark production on nuclear targets. All of the existing phenomenology of hard processes in nuclear collisions would be ruined;

of particular importance for the subject of this Workshop would be that the "$\bar{c}c$ absorption" picture of J/ψ suppression in pA and AB collisions would have to be abandoned, since all of the existing calculations rely on factorization in computing the initial yield of heavy quarks.

However, I think we are still far from reaching these, rather dramatic, conclusions, since it is not yet clear that the origin of the intermediate mass enhancement is indeed the enhancement of the total yield of open charm. Other possibilities, including redistribution of heavy quarks in phase space to enhance the dilepton yield in the NA50 coverage[5], secondary meson-meson interactions, and perhaps other novel phenomena have to be carefully considered before the enhancement of open charm is considered to be reliably established. Of course, a *direct* measurement of open charm yield would be extremely desirable to clarify the situation. In my opinion, this measurement should be considered as a high priority experiment for the future heavy ion program – it would dramatically reduce the amount of uncertainty we have to face at present.

The eagerly awaited data on charmonium production were presented at the Workshop by **M. Gonin**. The data confirmed the presence of strong J/ψ suppression in Pb-Pb collisions, going way beyond the expected on the basis of extrapolation of pA and S-U results. Also presented were the distributions of J/ψ's and Drell-Yan pairs as a function of the produced transverse energy, which carry a significant amount of additional, as compared to $J/\psi/DY$ ratios, information. These data, not surprisingly, triggered the next round of hot discussions at the Workshop. **A. Capella** suggested that the "discontinuity" observed in the $J/\psi/DY$ ratio was only apparent, since it was less pronounced in the J/ψ distribution in E_T taken separately. The discussion which followed clearly demonstrated that the E_T distributions of J/ψ's and Drell-Yan pairs contain far more information than the ratios themselves. In particular, Drell-Yan pair E_T distributions reflect the correspondence between the number of binary collisions (since the number of Drell-Yan pairs is determined by them) and the amount of produced transverse energy E_T. This correspondence is a very sensitive measure of the hadron production dynamics, and can be used to test the scaling of the number of produced hadrons with the number of participants (or binary collisions), which is significantly different for various models. In a calculation presented by Capella, the number of produced hadrons was evaluated as a sum of two terms – the first was proportional to the number of participants and the second – to the number of binary collisions. Since the number of binary collisions significantly increases in going from S-U to Pb-Pb, both the number and the density of the produced hadrons significantly grow, and it becomes possible to explain the *absolute magnitude* of the observed suppression. Of course, the model does not predict any discontinuities or

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structures in J/ψ yield as a function of E_T, and experimental confirmation (or disproof) of the existence of such structure becomes quite important. It is also important to remember that even under the most dramatic assumptions about the J/ψ suppression as a function of energy density, the fluctuations in the correspondence between E_T and the impact parameter significantly smear out the discontinuity in the J/ψ survival probability. Therefore, when looked at a higher resolution (more bins in E_T) the discontinuity in the observed J/ψ distribution would be somewhat washed out, but would still possess a rather distinctive structure. Even if this structure were not present in the data, we still need to check if the models invoked to explain the magnitude of the suppression are consistent with *all* of the observations, including the Drell-Yan pair and J/ψ E_T distributions, minimum bias E_T distributions and the correlation between the transverse E_T and forward E_{ZDC} energy.

The possibility to explain the Pb-Pb data in the framework of conventional models was also discussed by **R. Vogt**. The model with "comover" absorption was considered, with the conclusion that this model was incapable of describing even the absolute magnitude of the observed suppression. Similar conclusion has also been reached in a different approach by **C.-Y. Wong**. Clearly, we have to continue scrutinizing the existing models and confronting them with all of the available experimental data.

One of the crucial inputs to the "comover" calculations is the value of the J/ψ absorption cross section in its interactions with mesons. Theoretical predictions for this quantity differ by almost three orders of magnitude (see e.g. Ref. [6] and Ref. [7]). A new calculation was presented at the Workshop by **B. Müller**. It is based on the evaluation of the diagrams with $t-$ channel D meson exchange, contributing to the exclusive processes of J/ψ dissociation, e.g. $J/\psi + \rho \rightarrow D + \bar{D}$. The reasonable values of the corresponding coupling constants lead to the dissociation cross section which in the relevant energy region is on the order of 0.1 mb. It had been noted however that the D meson exchanged in the $t-$channel of the dissociation process is far off its mass shell. This has two implications: first, one has to consider heavier $(D^*, ...)$ exchanges, and second, one has to take account of the form factors. Little is known about the $t-$dependence of D meson couplings, but a conservative guess leads to the reduction of the cross section by an order of magnitude. The resulting absorption cross section then becomes on the order of 0.01 mb, which is a value fully consistent with the results of Ref. [6]. It should be noted that in both approaches the smallness of the dissociation cross section stems from the large mass of the charm quark mass. If the cross section is indeed so small, the rate of J/ψ dissociation in a hadron gas is negligible. It would be important to measure the J/ψ dissociation cross section at small energy

directly, either in the inverse kinematics experiment, or in the experiment utilizing Fermilab antiproton accumulator and nuclear jet target to produce low-momentum (~ 4 GeV/c) J/ψ's in the process $\bar{p}A \rightarrow J/\psi + (A-1)$.

Another effect potentially contributing to the suppression of J/ψ production – depletion of the gluons in nuclear medium – was discussed by **R. Hwa**. This approach is based on the observation that at high energies, because of the Lorentz factor, the time during which the nucleon traverses the nucleus is shorter than it takes for a signal to propagate through the nucleon's transverse size. This implies that one can distinguish between the interactions of (anti)quarks and gluons from the incident nucleon. Because of the larger color charge, the gluons are expected to interact stronger than the quarks inside the nucleus – the nucleus therefore can act as a gluon filter! Since the Drell-Yan pairs are produced (in the leading order in α_s) by the quark-antiquark fusion, and the heavy quarks by the gluon-gluon fusion, one can try to reconcile the absence of initial state effects in Drell-Yan pair production with the strong suppression observed for the J/ψ even though the Drell-Yan data still do impose an important constraint on the model.

Besides J/ψ suppression, this mechanism should also cause suppression of the open charm production in pA and AB collisions. Even though the current data do not seem to show such suppression, more data, particularly on correlated $\bar{D}D$ production, are needed to clarify the issue. Nevertheless, before such data become available, one can also argue in favor of *universality* of quark and gluon depletion in nuclear matter at small x (high energies and central region), which implies that the initial-state gluon absorption (or energy loss) is unlikely to be *the* mechanism responsible for the observed J/ψ suppression. Indeed, the virtuality ordering in the QCD DGLAP evolution means that at small x, the heavy quarks and Drell-Yan pairs are generated *at the very end* of the parton ladder; the evolution at the preceding stages of the parton cascade is identical in both cases. Moreover, the gluons fusing to form a heavy quark pair, or quarks and antiquarks annihilating into a Drell-Yan pair, have a large virtuality and, at small x, small momentum – therefore, they almost do not propagate inside the nucleus! The situation will change, however, if we move out of the central region, since either x_p or x_t will then become large, involving the valence partons in the production process – in this case the nucleus can indeed act as a gluon filter, suppressing gluon–induced processes stronger than the processes induced by the valence quarks. This is a very interesting topic to study!

The formation time effects in the production of Drell–Yan pairs were addressed at the Workshop by **J. Kapusta**. The motivation for this study is a well–known discrepancy between the Drell–Yan data and the predictions of

probabilistic cascades. In a typical cascade calculation, the nucleon loses energy immediately after an inelastic collision with a nucleon inside the nuclear target. Since at CERN SPS and Fermilab fixed target experiments we are still in the energy range where the Drell–Yan production cross section is a steep function of the incident nucleon's momentum, this initial state energy loss will lead to a strong suppression of the Drell–Yan production. This strong suppression in the Drell–Yan yields, however, is not seen experimentally, and this is a major problem for the probabilistic cascades. Even though this problem is well–known to insiders, so far this failure was not clearly acknowledged and documented by a direct comparison of a cascade calculation to the data. This comparison was shown at the Workshop by Kapusta, who demonstrated that a cascade calculation with energy loss under-predicts the Drell–Yan yields by a factor of up to ~ 3. It has also been stressed that this problem is a direct consequence of quantum mechanics, and to solve it within a cascade calculation, one has to simulate quantum–mechanical effects. This has been done by introducing the formation time, during which the incident nucleon does not "know" yet whether the energy has been lost. J/ψ suppression in the framework of a different numerical cascade model was presented at the Workshop by **J. Geiss**.

The difficulties of conventional approaches motivated several theorists to propose that the J/ψ suppression observed in Pb-Pb collisions is, after all, the signal of deconfinement, as was originally proposed[2]. An interesting realization of the deconfinement scenario was presented at this Workshop by **E. Shuryak**; in this approach, the produced deconfined phase reaches its "softest point" at some centrality in Pb-Pb collisions. This leads to a very long lifetime of the produced plasma, which can therefore effectively dissociate the produced J/ψ's. A distinctive feature of this approach is that the J/ψ absorption is maximal at some value of centrality, corresponding to the "softest point" of the equation of state of the produced deconfined phase; once the centrality increases further, the J/ψ survival probability increases again. However, also in this approach, the sharp discontinuity is difficult to explain, and we are still left with the "jump puzzle".

An approach aiming at the explanation of the observed structure in the J/ψ survival probability was presented in the talks of **M. Nardi** and **H. Satz**. In this approach, one considers the strings produced in nucleon-nucleon interactions in the transverse plane. Each of the strings is characterized by some transverse size, and when the density of strings becomes large enough, they "percolate", forming connected clusters. The assumption then is that this percolation corresponds to the formation of deconfined matter in which the J/ψ's are dissociated. While this is an interesting and attractive picture, a number

of questions have to be answered. The first, and most natural, question concerns the nature of "strings": do they represent inherently soft interactions, or perhaps mini-jets? (In the latter case the transverse size of the "string" would be determined by the transverse momentum of the produced mini-jet, $r_\perp \sim 1/k_\perp$.) It is also not clear why the number of produced "strings" is proportional to the number of collisions, while the number of produced secondaries looks to be proportional to the number of "wounded" nucleons. One can argue that the strings can fuse, but this would imply a very strong interaction among them, which is not taken into account in the percolation picture. On the other hand, in the independent string picture, it is unclear how the strings can fuse. Despite of these questions, the percolation provides an attractive and potentially enlightening framework for the description of deconfinement in heavy ion collisions, which has to be investigated in more detail.

Most of the issues described above were the subject of hot debates during the round table discussion led by **M. Gyulassy**.

3   The future of quarkonium

The future of quarkonium physics was addressed at the Workshop by **Y. Akiba, T. LeCompte, C. Lourenço** and **M. Rosati. Y. Akiba and M. Rosati** discussed the capabilities of the PHENIX detector at RHIC in doing quarkonium physics. With the possibility to reconstruct approximately half a million of J/ψ's in the dimuon decay mode, and fifty thousand in the dielectron decay during one year of running, the future of quarkonium physics at RHIC looks very bright. The PHENIX program will be nicely supplemented by the quarkonium program of STAR, as was discussed by **T. LeCompte**. STAR will be able to detect J/ψ's at high transverse momentum in the dielectron decay mode – for the first time in the history of J/ψ suppression in nucleus-nucleus collisions, we are going to have two independent experiments producing the data which can actually be compared and checked against each other! At RHIC we will finally gain access to the study of Υ suppression in nuclear collisions; the expected statistics – about one thousand events per year in the dimuon mode, as given by **M. Rosati** for the PHENIX acceptance – is more modest here, but it would be very interesting to glean at least some information about the flavor dependence of quarkonium suppression. Since the Υ is very tightly bound and has the binding energy more than twice larger than that of the J/ψ, it would probe the presence of very hard gluons in the medium; in the thermal picture, the dissociation of the Υ would require extremely high temperatures. As was noted by **Y. Akiba**, quarkonium production in polarized pp collisions will help to understand better the production

mechanism. **C. Lourenço** presented a summary of the experimental results on J/ψ production, and outlined the issues of potentially large importance for quarkonium physics at colliders – notably, the necessity to be able to separate direct charmonium production from that resulting from B decays.

Of course, the expected rates of J/ψ production at RHIC depend crucially on the magnitude of the suppression. In the most optimistic (for theorists) scenario of strong suppression, one may even wonder if there will be enough J/ψ's to detect. I do not think, however, that the experimentalists should worry about this – even if *all* of the J/ψ's inside the quark–gluon plasma are absorbed, we have to remember that, as evidentiated by the Tevatron results, at high p_t most of the J/ψ's are the products of the fragmentation of high–p_t gluons. Since any number of rescatterings inside the plasma will not affect the probability of the gluon fragmentation to a J/ψ, there would be a component in J/ψ production that will survive even in the most central collisions. However the re-scatterings inside the system can change the p_t distribution of the gluons, and therefore the resulting p_t distribution of the produced J/ψ's, shifting them to smaller momenta. Therefore, at high p_t J/ψ production at collider energies may be sensitive to the gluon energy loss. The corresponding theory and phenomenology still have to be developed.

One should also remember that at collider energies, we will enter the gluon shadowing domain in J/ψ production, and the shadowing will become important even for the production at central rapidity. To separate the shadowing effects, we would certainly need to have pA data as well. And, to have a proper reference point, the pp data on quarkonium production in both unpolarized and polarized collisions are indispensable.

The Workshop in Seattle has shown that the physics of heavy quarkonium continues to develop at a fast pace; moreover, we have every reason to believe that the next year, with RHIC turning on, will mark the beginning of the new exciting era in this field.

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